

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

NSN 7540-01-280-5500

**Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. Z39-18
298-102**

Enclosure 1

20040113 046

REPORT DOCUMENTATION PAGE (SF298) (Continuation Sheet)

(1) Statement of Problem Studied

Rare earth (RE) doping of GaN (and alloys with AlN and InN) has led to a new electroluminescent emission materials system at wavelengths covering the entire visible spectrum and portions of the ultraviolet and infrared spectra. GaN films doped with Eu, Er, and Tm dopants emit pure red, green, and blue (RGB) emission colors, respectively. In addition, Er-doped GaN emits strongly at $1.5 \mu\text{m}$. As a host for RE luminescent centers, GaN possesses many properties that are ideal for bright multiple color light emission. Specifically, GaN has excellent high field transport characteristics, it is chemically and thermally rugged, and it incorporates well the RE dopants. X-ray absorption measurements have shown that even at RE dopant levels exceeding 1 at. % the majority of RE dopants occupy a strongly bonded substitutional site on the Ga sublattice. According to RE crystal field theory this tetrahedrally bonded site allows optical activation and emission from RE 4f-4f inner-shell electronic transitions. Monte Carlo calculations of GaN carrier transport have shown that at $\sim 2 \text{ MV/cm}$ applied field the average electron possesses 2.6 eV energy that is adequate for exciting blue emission. GaN:Er devices have exhibited a brightness of 500-1000 cd/m^2 at $\sim 540 \text{ nm}$. In addition to pure colors, mixed colors can be achieved by doping with a combination of REs. For example, co-doping with Er and Tm results in an emission spectrum that is perceived by the human eye as a blue-green (turquoise) hue. Multiple color capability in a single device has also been demonstrated by adjusting the bias voltage (in a co-doped GaN:Er,Eu layer) or by switching the bias polarity (in a stacked two layer GaN:Er/GaN:Eu structure). The combination of pure or mixed color emission, the availability of bias controlled color, and the potential for white light emission indicate that GaN:RE devices have enormous potential for display applications. The strong emission at $1.5 \mu\text{m}$ from GaN:Er devices also indicates important potential for telecommunication applications.

(2) Summary of Most Important Results

As shown in Fig. 1, visible {red, green, and blue (RGB)} and infrared emission can be obtained from rare earths (REs) in-situ doped during growth into films of the III-V semiconductor GaN. Multiple color capability is a primary requirement for flat panel displays (FPDs) and agile visible and IR light sources.

This program has produced significant advances in GaN:RE science and device technology: (a) we have developed a working model for the in-situ RE doping of GaN during MBE growth; (b) we have developed GaN:RE device fabrication techniques; (c) we have developed a variety of GaN:RE thin film electroluminescent devices (ELDs).

A brief review of the GaN host properties which result in bright, multiple color capability is given in Sec. 2.1 below. GaN incorporates very well RE dopants and can provide hot carriers with average energies corresponding to excitation of blue emission, as discussed in Sec.2.2. For the GaN:RE material system the possibility of multiple color indicators which change color based solely on the polarity or magnitude of applied bias is also of great interest. In Sec. 2.3, a summary of results on voltage controlled-(VC)-ELDs and on switchable color (SC)-ELDs is presented. The VC-ELDs progress from

red to green emission with increasing bias voltage whereas the SC-ELDs switch from red to green emission based on the polarity of applied bias. Normalized red (Eu), green (Er), and blue (Tm) emission spectra of individual GaN:RE ELDs are shown are shown in Fig. 1. Also shown is the \sim 1550 nm emission from GaN:Er which is of particular interest in telecommunications applications.

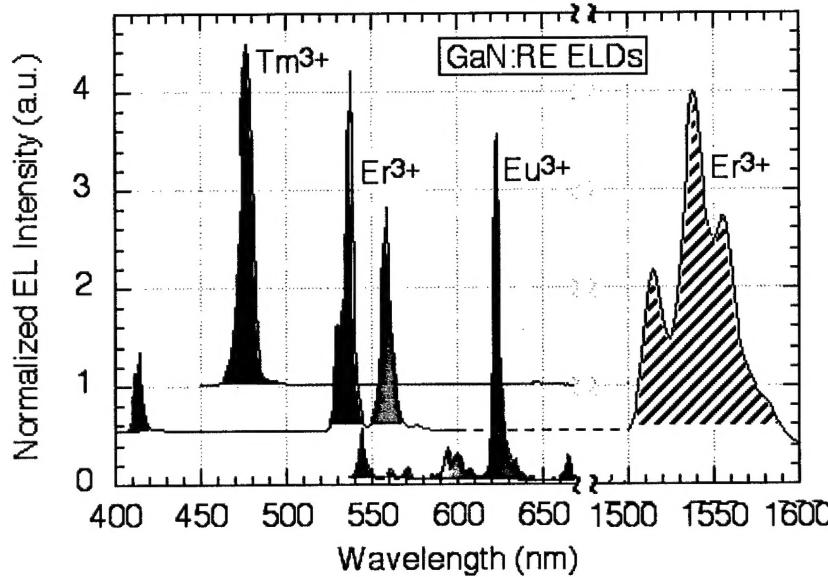
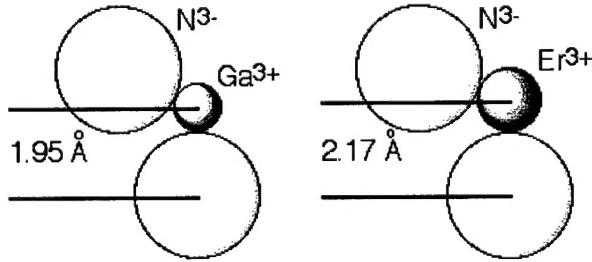


Fig. 1

The emission spectra of Tm, Er, and Eu-doped GaN ELDs showing the visible and IR wavelengths of interest. The visible peaks for each RE correspond to saturated RGB colors which can be utilized for single-, multiple-, mixed-, and full-color applications. The \sim 1550 nm emission from GaN:Er is of particular interest in telecommunications applications.

2.1 Rare-Earth-Doped Nitride Material system

The RE-doped GaN is grown in a Riber MBE-32 system on 2 in. p-Si (111) substrates. Ga and RE solid sources are used in conjunction with a RF plasma source supplying atomic nitrogen. For GaN:RE ELD operation indium-tin-oxide (ITO) ring contacts fabricated on the GaN:RE layer. Low voltage GaN:Er ELDs have demonstrated green emission at 5 V DC bias. High brightness GaN:Er ELDs biased with 50-100 V have exhibited a brightness as high as 500-1000 cd/m². The intense light emission from GaN:RE ELDs can be partially attributed to the ability of GaN to incorporate large concentrations of optically active RE species. In other semiconductor hosts (such as Si, GaAs), high RE concentrations result in quenching of the emission due to degradation of the host material and or RE precipitation. This ability to incorporate large RE concentrations in GaN is surprising when considering the size mismatch between RE ions and the Ga³⁺ cation, which is larger than in II-VI hosts. For comparison some relevant effective ionic radii are listed for Er-doped GaN, Si, ZnS, SrS, and AlN in the table at the right of Fig. 2.



Effective Cation Mismatch			
Ga ³⁺	0.47	N ³⁻	1.44
Si	1.18	Er ³⁺	0.78
Zn ²⁺	0.60	S ²⁻	^{no data}
Sr ²⁺	1.18	S ²⁻	1.84
Al ³⁺	0.39	N ³⁻	1.44
		Er ³⁺	0.78
		(CN=4)	(CN=10)
		(CN=4)	(CN=6)
		(CN=4)	

Fig. 2 Drawing (left) indicating experimental data for the Ga-N and Er-N bond length and atomic radii in wurtzite GaN:Er. Table (right) of effective ionic radii and coordination number (CN) for Er-doped GaN, Si, ZnS, SrS, and AlN.

An X-ray absorption study of GaN:Er reveals that even at high Er concentrations (>0.1 at. %) the majority of Er ions sit substitutionally on the Ga sublattice. The experimental data for the Ga-N and Er-N bond lengths are reflected in the drawing at the left of Fig. 2.

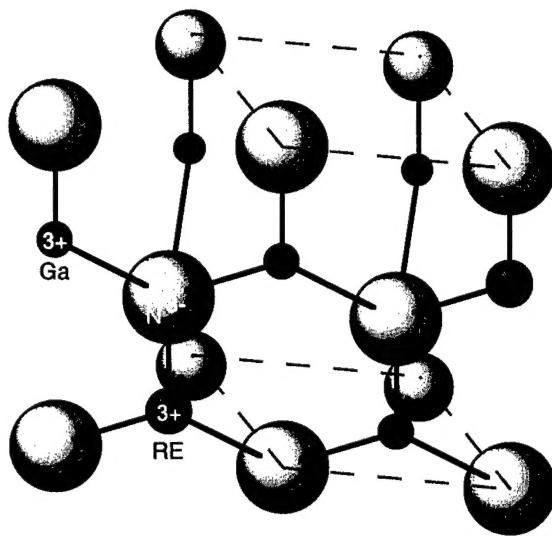


Fig. 3 Simple model of GaN:RE crystal structure showing the RE dopants on Ga sub-lattice locations.

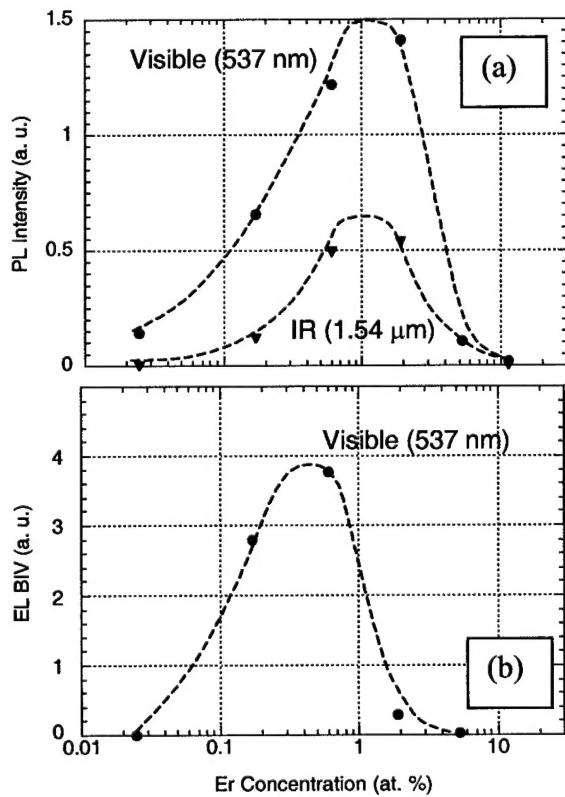


Fig. 4 PL and EL intensity vs. Er concentration: (a) visible and IR PL intensity; (b) current normalized visible EL (BIV).

In this Ga substitutional site (see Fig. 3) the tetrahedral bonding about the RE lacks inversion symmetry and results in allowance of normally forbidden RE intrashell $4f$ - $4f$ transitions which in turn result visible light emission. GaN can incorporate RE concentration at levels comparable to or greater than that possible with commercial II-VI hosts. This is partially due to the strong bonding nature of GaN (partially covalent) compared to the more weakly bonded II-VI compounds (largely ionic). The experimentally measured Er-N bond length of 2.17 Å is very short, a testament to its bond strength. GaN also possesses the ability to incorporate the trivalent RE ions without violating charge neutrality. Incorporating RE^{3+} in II-VI phosphors such as ZnS:Tb requires co-doping with F or O in order to satisfy charge neutrality and to achieve the best luminance and efficiency values. As shown in Fig. 4, the optimum RE dopant levels in GaN is around 1%, confirming that GaN is an excellent host for allowing large concentrations of RE dopants without severe quenching of light emission. The bonding for all RE elements is roughly similar since they all share an identical outer shell ($5s^2 5p^6$). This enables straight forward multiple color capability through co-doping GaN with several RE species. The well studied RE $4f$ - $4f$ transitions provide several choices of RE dopant in GaN in order to create red (Eu, Pr, Sm), green (Er, Tb), blue (Tm) light and potentially white (Ho, multiple RE's) light.

2.2 Hot carrier generation

TFEL hosts such as GaN distinguish themselves from phosphors utilized in CL or PL based light emission by their high field electronic transport mechanisms. TFEL hosts need to be able to provide hot carriers with greater than 2 eV energy at an applied field of 1-2 MV/cm. This requirement has limited efficient TFEL hosts to wide band gap semiconductors.

Fig. 5 shows a qualitative plot of electron energy distribution in GaN at several applied field strengths. The pictured electron distributions are presented accurately in average energy only, as taken from Monte Carlo calculations of high field transport in GaN. The calculations show that at ~ 2 MV/cm applied field the average carrier energy is equal to that required for exciting blue (2.6 eV) emission. Also plotted in Fig. 5 is an approximate curve for the Er impact excitation cross-section of the $^2\text{H}_{11/2}$ level which results in green (~ 2.3 eV) emission. If full color capability is to be achieved in a single host, carrier energies nearing 3 eV are required. Currently, the TFEL host SrS, a II-VI compound, most efficiently provides hot carrier excitation with sufficient energy for blue emission. SrS:Cu,Ag and SrS:Ce are excellent blue and blue-green emitters but there does not exist a bright red SrS-based TFEL phosphor in order to realize full color capability in a single host. GaN:RE could potentially provide an efficient *full-color* phosphor based on a single host.

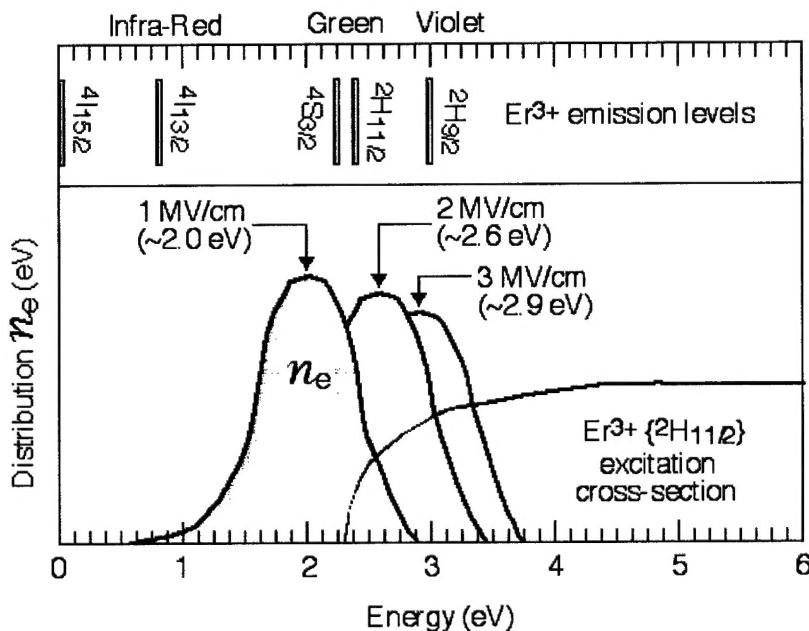


Fig. 5

Qualitative plot of electron energy distribution for 1, 2, and 3 MV/cm applied field to GaN. The pictured electron distributions are estimated based on average energy only, as determined¹² from Monte Carlo calculations of high field transport in GaN. Also shown is an approximate curve for the Er impact excitation cross-section of the $^2\text{H}_{11/2}$ which results in green (~ 2.3 eV) emission. The corresponding energy levels of dominant emissions from Er^{3+} are also shown at the top of the plot.

Carrier transport mechanisms for field strengths on the order of \sim MV/cm are not fully understood at the theoretical level. However, experimental data can be utilized to provide insight into high field transport behavior. A lanthanide (RE) doping study comparing ZnS and SrS hosts indicates that SrS is a superior material for blue TFEL. In that study the distribution of high energy carriers is obtained approximately by examining the existence and/or strength of blue and violet emission peaks compared to lower energy green, red and IR peaks. We have applied this approach to the evaluation of GaN:Er and GaN:Tm ELDs. The GaN:Er spectrum in Fig. 1 is taken at ~ 1.5 MV/cm applied field and exhibits a strong emission peak in the violet spectrum (415 nm). Referring to Fig. 5, this 415 nm peak represents a photon energy of ~ 3 eV corresponding to the $^2\text{H}_{9/2}$ Er level. This brings the qualitative plots of electron energy distribution into agreement with the observed GaN:Er spectra. For II-VI hosts the ZnS:Er spectrum saturates in the green, whereas SrS:Er has very strong violet peaks. Unlike the case of ZnS:Tm where most of the light emitted is in the IR, GaN:Tm ELDs emit a 477 nm blue emission twice as strong as the emission at 801 nm. Phosphor crystallinity can also play a major role in high field transport. For vertically biased GaN:RE ELDs fabricated with a conductive substrate as the bottom electrode, the tendency of growth in vertical columns is advantageous for high field transport since the number of grain boundaries hot carriers intercept is reduced. In summary, GaN provides adequate hot

carrier distributions for excitation of multiple color RE light emission spanning the entire visible spectrum.

2.3 Tunable and switchable-color ELDs

Given the ability of GaN:RE phosphors to emit light at multiple wavelengths some novel devices can be considered which allow bias control of the emitted color. One such TFEL device structure utilizes stacked individual color ELDs. For this style of multiple-color stacked device, the ability to independently drive 2 distinct light emitters (such as red and green) normally requires 3 electrical contacts. We have developed GaN:RE ELDs which can emit multiple colors by varying only the electrical bias on two electrodes. The first approach is based on a single GaN film co-doped with Eu and Er. The VC-ELD structure is shown in Fig. 6b. During operation, the emission from VC-ELDs can be adjusted from orange light emission (primarily Eu red, Fig 6b) to yellow emission (combination of Eu and Er green, Fig. 6a) by merely increasing the applied voltage from -70 V to -100 V. The progression from orange to yellow color is likely attributed to differences in impact excitation cross-section parameters. Red emission from Eu with a long excited state lifetime (5D_0 - 7F_2 , ~ 1 ms) should saturate with increasing bias current before Er green emission with its shorter lifetime ($^2H_{11/2}$ - $^4I_{15/2}$, ~ 0.01 ms). Also, green emission (~ 2.3 eV) requires hotter carriers (higher applied voltage) than red emission (~ 2.1 eV). Other effects such as temperature quenching could also give rise to the voltage control of emission color

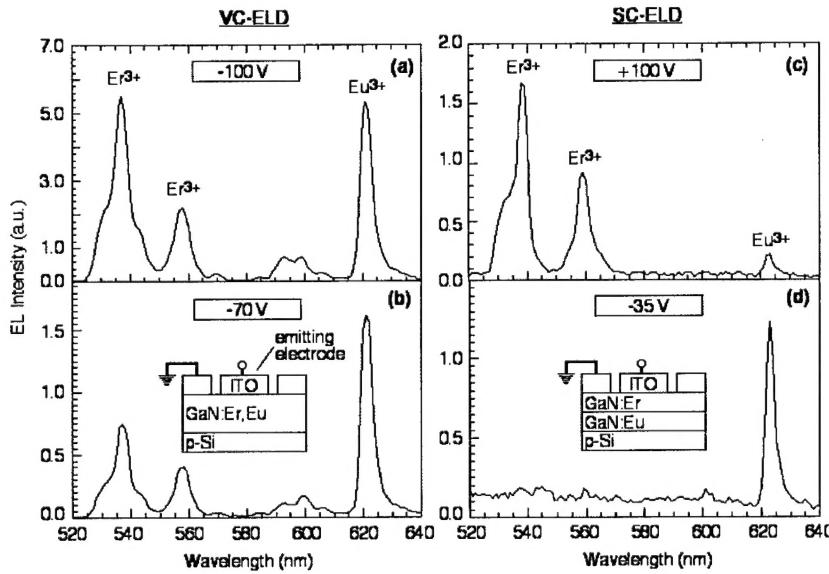


Fig. 6

(a, b) EL intensity measured from an ITO/GaN:Er,Eu/p-Si VC-ELD for -70 V (orange) and -100 V (yellow) bias applied to the emitting electrode.

(c, d) EL intensity measured from ITO/GaN:Er/GaN:Eu/p-Si SC-ELD for $+100$ V positive (green) and -35 V negative (red) bias applied to the emitting electrode.

SC-ELDs have also been developed utilizing the GaN:Er/GaN:Eu stacked phosphor structure shown Fig. 6d. The SC-ELDs switch from red to green emission by changing the polarity of the applied voltage: positive bias ($+100$ V, 0.45 mA) for saturated green emission and negative bias (-35 V, -2.5 mA) for red. Some of the same underlying effects attributed to color change in VC-ELDs also likely play a role in the SC-ELDs. However, the dominant influence on color switching in SC-ELDs is attributed to polarity dependent current paths through the stacked phosphor layers. In comparison to VC-ELDs the SC-ELDs do not allow tuning of color emission but do have the advantage of a remarkable ~ 10 X contrast between emission modes. Application of the simple SC-ELD structure to switching between other visible and/or infrared wavelengths is envisioned based on appropriate choice of RE dopants in the GaN layers.

2.4 Full color capability

One of the ultimate goals beyond multiple color capability based on GaN:RE is the prospect of full color (or white light) capability through additive light generation from integrated RGB ELDs or subtractive light generation from a codoped (GaN:Eu,Er,Tm) or stacked phosphor (GaN:Eu/GaN:Eu/GaN:Tm). Regardless of phosphor layer format, the individual GaN:RE phosphors are ideal for full color capability since the spectra are characterized by sharp dominant peaks well-matched to the definition of saturated RGB colors. This is a clear advantage for GaN:RE over many phosphors which have broad or multiple peak emission spectra which require filtering in order to generate a saturated RGB color. The full color capability of GaN:RE ELDs is illustrated using the CIE chromaticity diagram shown in Fig. 7. The triangle in the diagram connects and defines the full color capability of emission from GaN doped with Tm (blue), Er (green), and Eu (red). For comparison, commercial II-VI TFEL phosphors and CRT phosphors are incorporated into the diagram also. The II-VI TFEL and CRT phosphors provide adequate full color capability. The color triangle defined by GaN:RE phosphors encapsulates almost all of the commercialized II-VI TFEL and CRT phosphors and provides superior color capability. Based on recent successes with orange GaN:Er,Eu and turquoise GaN:Tm,Er ELDs, we expect that proper mixing of RE dopants in a GaN:Er,Eu,Tm ELD should result in white light emission. Therefore, emission of any color is envisioned possible based on TFEL of GaN doped with multiple RE dopants.

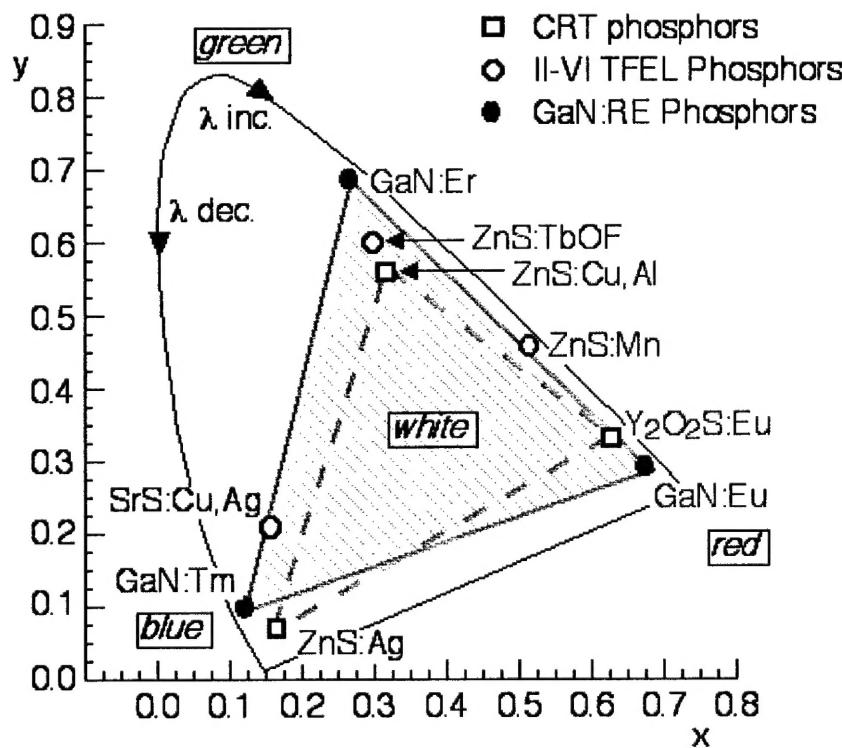


Fig. 7

CIE x-y chromaticity diagram showing the location of RGB GaN:RE ELDs (closed circles). Also shown are the coordinates of other commercial II-VI TFEL phosphors (open circles) and CRT phosphors (open squares). In addition to primary colors, mixed colors or white light can be obtained by mixing relative intensities found within the triangle defined by the individually colored constituents.

(3) List of All Publications

1. J. Heikenfeld, D. S. Lee, M. Garter, R. Birkhahn, and A. J. Steckl, "Low Voltage GaN:Er Electroluminescent Devices", *Appl. Phys. Lett.* Vol. 76 (11), pp. 1365-1367, March 2000.

2. U. Hommerich, J. T. Seo, C. R. Abernathy, A. J. Steckl, and J. M. Zavada, "Spectroscopic Studies of the Visible and Infrared Luminescence from Er-doped GaN", Materials Science & Eng. B, Vol. 81/1-3, pp. 116-120, May 2001.
3. A. J. Steckl, J. Heikenfeld, D. S. Lee and M. Garter, "Multiple Color Capability from Rare Earth Doped Gallium Nitride", Materials Sci. & Eng. B, Vol. 81/1-3, pp. 97-101, May 2001.
4. J. Heikenfeld and A. J. Steckl, "Rare-Earth-Doped GaN Switchable Color Electroluminescent Devices", IEEE Trans. Electr. Dev. Vol. 49, pp. 1545-1551, Sept. 2002.
5. J. Heikenfeld and A. J. Steckl, "Alternating Current Thin Film Electroluminescence of GaN:Er", Appl. Phys. Lett. Vol. 77, pp. 3520-3522, Nov. 2000.
6. J. Heikenfeld and A. J. Steckl, "AC Operation of GaN:Er Thin Film Electroluminescent Display Devices", Mat. Res. Soc. Symp. Vol. 639, pp. G10.4.1-6, Oct. 2001.
7. J. Heikenfeld and A. J. Steckl, "Electroluminescent Devices on Glass Using a High Temperature Stable GaN-based Phosphor and Thick Film Dielectric", IEEE Trans. Electr. Dev. Vol. 49 (4), pp. 557-563, April 2002.
8. D. S. Lee, J. Heikenfeld, A. J. Steckl, U. Hommerich, J. T. Seo, A. Braud, and J. M. Zavada, "Optimum Er Concentration for In-Situ Doped GaN Visible and Infrared Luminescence", Appl. Phys. Lett. Vol. 79, pp. 740-742, Aug. 6, 2001.
9. M. Garter and A. J. Steckl, "Temperature Behaviour of Visible and Infrared Electroluminescent Devices Fabricated on Er-doped GaN", IEEE Trans. Electr. Dev. Vol. 49 (1), pp. 48-54, Jan. 2002.
10. D. S. Lee and A. J. Steckl, "Room-Temperature-Grown Rare-Earth-Doped GaN Luminescent Thin Films", Appl. Phys. Lett. Vol. 79, pp. 1962-1964, Sept. 24, 2001.
11. J. Heikenfeld and A. J. Steckl, "Contrast Enhancement in Black Dielectric Electroluminescent Devices", IEEE Trans. Electr. Dev. Vol. 49, No. 8, pp. 1348-1352, Aug. 2002.
12. D. S. Lee, J. Heikenfeld and A. J. Steckl, "Growth-Temperature Dependence of Er-Doped GaN Luminescent Thin Films", Appl. Phys. Lett. Vol. 80, pp. 344-346, Jan. 21, 2002.
13. D. S. Lee and A. J. Steckl, "Ga Flux Dependence of Er-Doped GaN Luminescent Thin Films", Appl. Phys. Lett. Vol. 80, pp. 728-730, Feb. 4, 2002.
14. J. T. Seo, U. Hommerich, A. J. Steckl and J. M. Zavada, "Thermal Quenching of Photoluminescence from Er-doped GaN Thin Films", J. Alloys & Compounds, Vol. 341, pp. 62-66, July 2002.
15. D. S. Lee and A. J. Steckl, "Lateral Color Integration on Rare-Earth-Doped GaN Electroluminescent Thin Films", Appl. Phys. Lett. Vol. 80, pp. 1888-1890, Mar. 18, 2002.

16. C. C. Baker, J. C. Heikenfeld, and A. J. Steckl, "Photoluminescent and Electroluminescent $Zn_2Si_{0.5}Ge_{0.5}O_4:Mn$ Thin Films for Integrated Optic Systems", IEEE J. Selected Topics in Quantum Electronics, IEEE J. Selected Topics in Quantum Electronics, Vol. 8 (6), pp. 1420-1426, Nov/Dec. 2002.

17. Y. Wang and A. J. Steckl, "Three-color integration on rare-earth doped GaN electroluminescent thin films", Appl. Phys. Lett. Vol. 82 (3), pp. 502-504, 27 Jan. 2003.

18. A. J. Steckl, J. C. Heikenfeld, D. S. Lee, M. Garter, C. C. Baker, Y. Q. Wang, and R. Jones, Invited Paper, "Rare-earth-doped GaN: Growth, Properties and Fabrication of Electroluminescent Devices", IEEE J. Selected Topics in Quantum Electronics, Vol. 8 (4), pp. 749-766, July/Aug. 2002.

19. J. Zavada, U. Hommerich, and A. J. Steckl, "Excitation mechanisms of rare earth ions embedded in GaN thin films", Electrochem. Soc. Meeting Proc. Vol. 2002-3, May 2002.

20. D. S. Lee and A. J. Steckl, "Enhanced Blue and Green Emission in Rare-Earth-Doped GaN Electroluminescent Devices by Optical Photopumping" Appl. Phys. Lett. Vol. 81 (13), pp. 2331-2333, 23 Sept. 2002.

21. D. S. Lee and A. J. Steckl, "Effect of Growth Temperature on Blue Emission from GaN:Tm Electroluminescent Devices", Appl. Phys. Lett., Vol. 82 (1), pp. 55-57, 06 Jan. 2003.

22. A. J. Steckl, J. C. Heikenfeld, D. S. Lee, Y. Q. Wang, and R. Jones, "Rare-earth-doped GaN Phosphors: Growth, Properties and Fabrication of Electroluminescent Devices", Proc. Electroluminescence 2002, Ghent, Belgium, Sept. 2002.

23. E. E. Nyein, U. Hommerich, J. Heikenfeld, D. S. Lee, A. J. Steckl, J. M. Zavada, "Spectral and Time-Resolved Photoluminescence Studies of Eu-doped GaN", Appl. Phys. Lett., Vol. 82 (11), pp. 1655-57, 17 Mar. 2003.

24. F. Pelle, F. Auzel, J. M. Zavada, D. S. Lee, and A. J. Steckl, "Fluorescence Dynamics of Er^{3+} Ions in MBE-Grown GaN Thin Films", NATO Science Series Vol: Physics of Laser Crystals, 2003.

25. F. Pelle, F. Auzel, J. M. Zavada, D. S. Lee and A. J. Steckl, "New Spectroscopic Data of Erbium Ions in GaN Thin Films", Electrochem. Soc. Proc. Vol. 2003-04: pp. 235-257, April 2003.

(4) List of All Presentations

1. A. J. Steckl, R. Birkhahn, M. Garter, L. C. Chao, D. S. Lee, and J. Heikenfeld, "Rare Earth Activated GaN Light Emitting Devices", Int'l. Conf. on SiC and Related Materials, Research Triangle Park, NC (Oct. 1999).
2. J. Heikenfeld, M. J. Garter, D. S. Lee, R. Birkhahn, and A. J. Steckl, "Low Voltage GaN:Er Electroluminescent Devices", Materials Research Soc. Conference, Boston, MA (Dec. 1999).

3. M. J. Garter, B. K. Lee, R. Birkhahn, J. Heikenfeld, D. S. Lee, and A. J. Steckl, "Strong 1.5 μ m Emission from Er-doped GaN Electroluminescent Devices at 400K", Materials Research Soc. Conference, Boston, MA (Dec. 1999).
4. D. S. Lee, R. Birkhahn, J. Heikenfeld, M. J. Garter, and A. J. Steckl, "Mixed Color Emission from GaN co-doped with Er³⁺/Eu³⁺ or Er³⁺/Tm³⁺", Materials Research Soc. Conference, Boston, MA (Dec. 1999).
5. R. Birkhahn, J. Heikenfeld, M. Garter, D.S. Lee, A. J. Steckl, P.H. Citrin, P. A. Northrup, K. Lorenz, R. Vianden, M.F. da Silva, J.C. Soares, E. Alves, A. Saleh, J. M. Zavada, "Ga and Er Site Competition in GaN:Er Films Exhibiting Visible Luminescence", Materials Research Soc. Conference, Boston, MA (Dec. 1999).
6. U. Hommerich, J. T. Seo, J. D. MacKenzie, C. R. Abernathy, R. Birkhahn, A. J. Steckl, and J. M. Zavada, "Comparison of the Optical Properties of Er-doped GaN Prepared by Metalorganic and Solid Source MBE", Materials Research Soc. Conference, Boston, MA (Dec. 1999).
7. P. Citrin, P. A. Northrup, R. Birkhahn, and A. J. Steckl, "Er Local Structure in GaN by EXAFS Analysis", Physics of Compound Semiconductor Interfaces, Salt Lake City, Utah (Jan. 2000).
8. A. J. Steckl, "Optical Properties and Photonic Devices Using Rare-Earth-Doped GaN", Invited presentation, Colloquium on the Physics of Quantum Electronics , Snowbird, Utah (Jan. 2000).
9. P. H. Citrin, P. A. Northrup, R. Birkhahn, and A. J. Steckl, "Local Structure of Er in GaN:Er Films Exhibiting Visible Luminescence", American Physical Society March Meeting, Minneapolis, MI (March 2000).
10. A. J. Steckl, "Rare Earth Doped Gallium Nitride – A New Approach to the Pursuit of Light" Invited presentation, *Symposium on Electronic and Photonic Materials in the 21st Century*, Electrochemical Society Meeting, May 2000, Toronto.
11. A. J. Steckl, "Rare Earth Doped Gallium Nitride – Light Emission from the Ultraviolet to the Infrared", *Symposium on Rare Earth Doped Semiconductors*, European Materials Research Society Meeting, May-June 2000, Strasbourg, France (May-June 2000).
12. J. Heikenfeld and A. J. Steckl, "AC Operation of GaN:Er Thin Film Electroluminescent Display Devices", Materials Research Soc. Meeting, Boston, MA (Nov. 2000).
13. A. S. Mitofsky, G. C. Pappen, S. G. Bishop, D. S. Lee, A. J. Steckl, J. T. Seo, and U. Hommerich, "Comparison of Er³⁺ Photoluminescence and Photoluminescence Excitation Spectroscopy in In-Situ Doped GaN:Er and Implanted GaN", Materials Research Soc. Meeting, Boston, MA (Nov. 2000).
14. A. J. Steckl, "Excitation Mechanisms in Rare Earth Doped GaN Electroluminescent Devices", Invited Presentation, 31st Colloquium on the Physics of Quantum Electronics, Snowbird, Utah. (Jan. 2001).

15. A. J. Steckl, "Rare Earth Doped GaN Electroluminescent Devices", Invited Presentation, SPIE Photonics West Optoelectronics 2001, San Jose, CA (Jan. 2001).
16. A. J. Steckl, "Rare Earth Doped Gallium Nitride – Light Emission From Ultraviolet to Infrared", Seminar Presentation, Yale University, New Haven, CT (Feb. 2001).
17. E. E. Nyein, J. T. Seo, A. Blueitt, U. Hommerich, J. Heikenfeld, D. S. Lee and A. J. Steckl, "Optical Spectroscopy of Eu-doped GaN Prepared by Solid Source Molecular Beam Epitaxy", American Physical Society Meeting (March 2001).
18. D. S. Lee, J. Heikenfeld, M. Garter, A. J. Steckl, U. Hommerich, J. T. Seo, A. Braud, and J. Zavada, "Optimum Er Concentration for In-Situ Doped GaN Visible and IR Luminescence", 43rd Electronic Materials Conference, Notre Dame, IN (June 2001).
19. A. J. Steckl, J. Heikenfeld and D. S. Lee, "Rare-Earth-Doped GaN Phosphors for Electroluminescent Displays", Int'l. Conf. Sci. Tech. Emissive Displays, San Diego, CA (Nov. 2001).
20. D. S. Lee, J. Heikenfeld and A. J. Steckl, "Low-Temperature Growth of Rare-Earth-Doped GaN Luminescent Thin Films", Materials Research Soc. Meeting, Boston, MA (Nov. 2001).
21. A. J. Steckl, J. Heikenfeld, D. S. Lee, and C. Baker, "Rare Earth Doped Gallium Nitride – From Thin Film Growth to Photonic Applications", Invited Presentation, SPIE Photonics West, Optoelectronics 2002, San Jose, CA (Jan. 2002).
22. J. Heikenfeld and A. J. Steckl, "High Contrast Thick Dielectric Electroluminescent Displays on Glass Substrates", Intl. Symp. Soc. Information Display, Boston, MA (May 2002).
23. D. S. Lee and A. J. Steckl, "Photopump-Enhanced Emission of Rare-Earth-Doped GaN Electroluminescent Thin Films", Materials Research Soc. Meeting, Boston, MA (Nov. 2002).
24. Y. Q. Wang and A. J. Steckl, "Three-color Integration of Rare-Earth-Doped GaN Electroluminescent Thin Films", Materials Research Soc. Meeting, Boston, MA (Nov. 2002).
25. A. J. Steckl, J. Heikenfeld, D. S. Lee, M. Garter, C. Baker, Y. Q. Wang, R. Jones, and M. Pan, Invited Paper, "Rare-Earth-Doped GaN: Growth, Properties and Fabrication of Electroluminescent Devices", Materials Research Soc. Meeting, Boston, MA (Nov. 2002).
26. A. J. Steckl, C. Munasinghe, D. S. Lee, and J. Heikenfeld, "Emission Efficiency in Electroluminescent Devices", Workshop on Impurity Based Electroluminescence in Wide Bandgap Semiconductors, Santa Fe NM, April 2003.
- D. S. Lee, A. J. Steckl, E. E. Nyein, U. Hommerich, F. Pelle, and J. M. Zavada, "Enhancement of Blue Emission from Tm-Doped GaN Electroluminescent Devices", Workshop on Impurity Based Electroluminescence in Wide Bandgap Semiconductors, Santa Fe NM, April 2003.

(5) Scientific Personnel:

- Christopher Baker – **Ph. D. – 2003** - *Electroluminescent Thin Film for Integrated Optics Applications*
- Jason Heikenfeld – **Ph. D. – 2001** - *Rare Earth Doped Gallium Nitride Flat Panel Display Devices*
- Michael Garter – **Ph. D. – 2001** - *Electroluminescent Devices Fabricated on Erbium Doped GaN*
- Chanaka Munasinghe
- Don Lee – **Ph. D. – 2002** - *Growth and Mechanisms for Rare-Earth-doped GaN Electroluminescent Devices*
- John Wang
- Prof. A. J. Steckl

(6) Report of Inventions

- “Polarity-Controlled Color Switching Electroluminescent Devices”

Invention Disclosure: UC#99-048 – 10/25/99.

US Patent Application: Denied

- “Phosphors of Rare-Earth-Doped GaN for Thin Film Alternating Current Electroluminescent Devices”

Invention Disclosure: UC#100-062 – 10/19/00

US Patent Application: Denied

- “Electroluminescent Display Formed on Glass with a Thick Dielectric Layer”

Invention Disclosure: UC#100-065 – 11/17/00

US Patent Application: In Progress

- “Black or Color Dielectric for Electroluminescent Devices”

Invention Disclosure: UC#101-019 – 5/01/01

US Patent Application: Granted 10/21/03, Patent #6,635,306

- “Photopump Enhanced Electroluminescent Devices”

Invention Disclosure: UC#102-033 – 05/06/02

US Patent Application: In progress